The BTeV Experiment: Physics and Detector

FPCP 2003
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More details can be found at
www-physics.mps.ohio-state.edu/~klaus/research/cipanp.pdf and
the BTeV web site at fnal.gov

B Physics Today

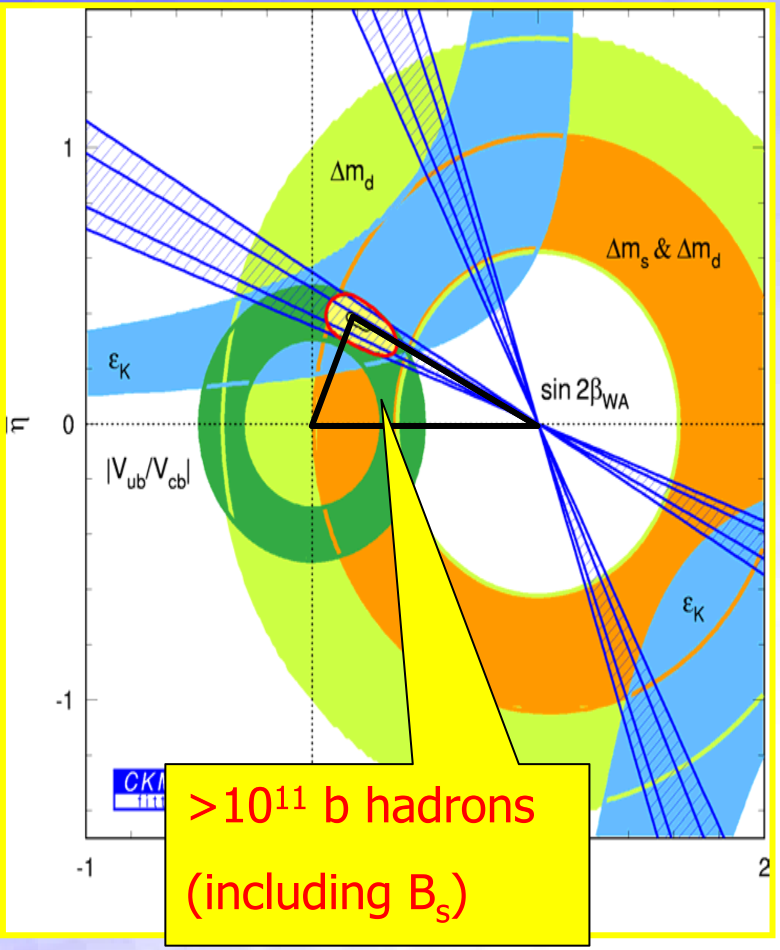
- CKM Picture okay

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- CP Violation observed

$\sin(2\beta) = 0.734 +/- 0.054$

- No conflict with SM

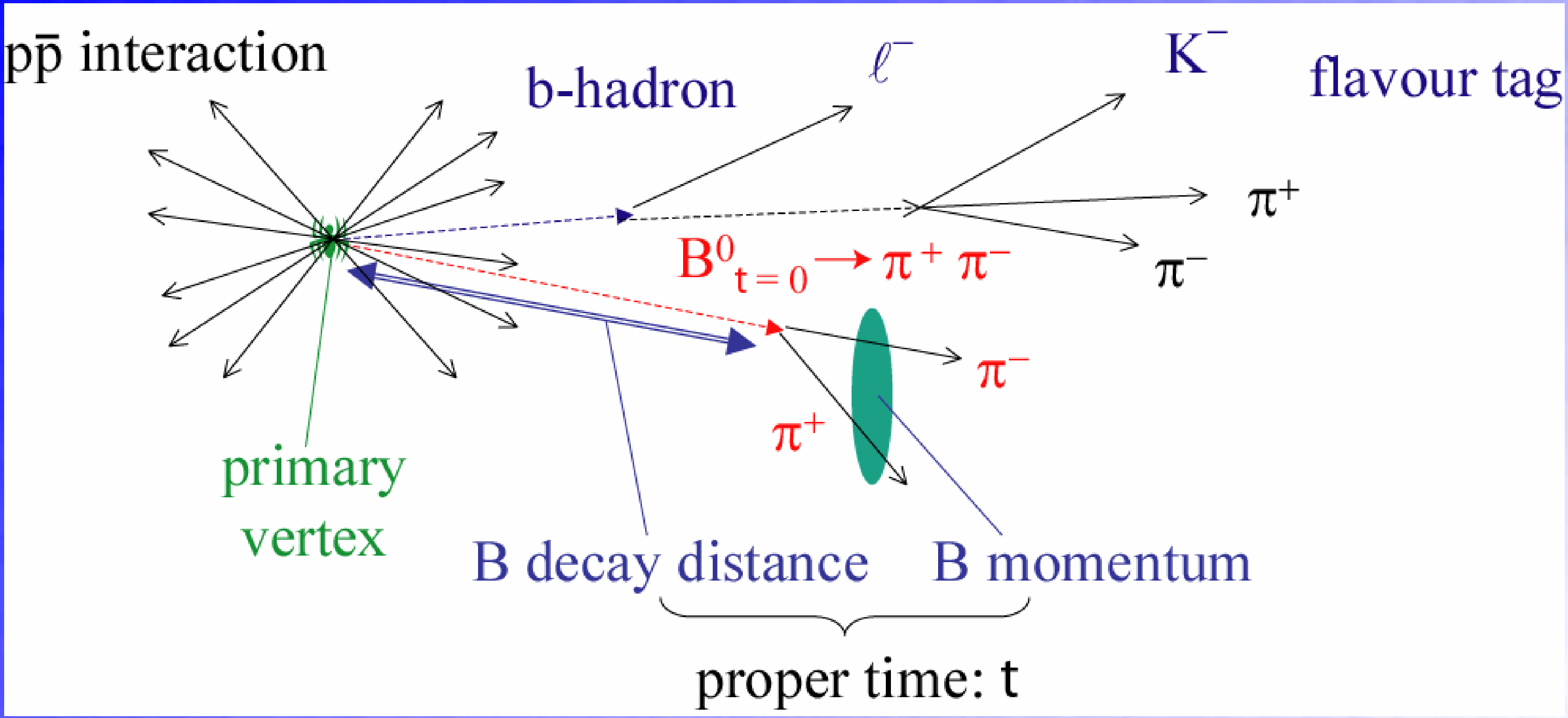


B Physics at Hadron Colliders

	Tevatron	LHC
Energy	2 TeV	14 TeV
b cross section	~100 μb	~500 μb
c cross section	~1000 μb	~3500 μb
b fraction	2×10^{-3}	6×10^{-3}
Inst. Luminosity	2×10^{32}	$>2\times10^{32}$
Bunch spacing	132 ns (396 ns)	25 ns
Int./crossing	<2> (<6>)	<1>
Luminous region	30 cm	5.3 cm

- ⇨ Large cross sections
- ⇨ Triggering is an issue
- ⇨ All b-hadrons produced (B, B_s, B_c, b-baryons)

Detector Requirements



- Trigger, trigger, trigger
- Vertex, decay distance
- Momentum
- PID
- Neutrals (γ, π^0)

From F. Teubert

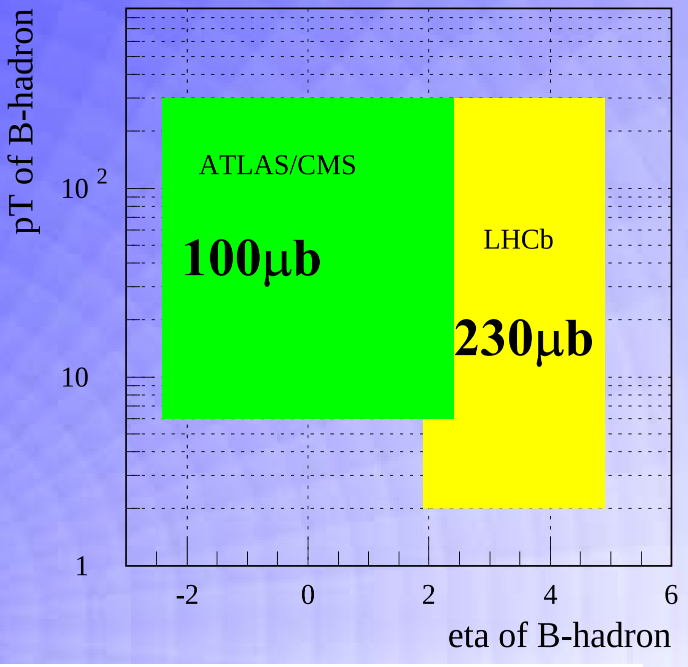
Forward vs. Central Geometry

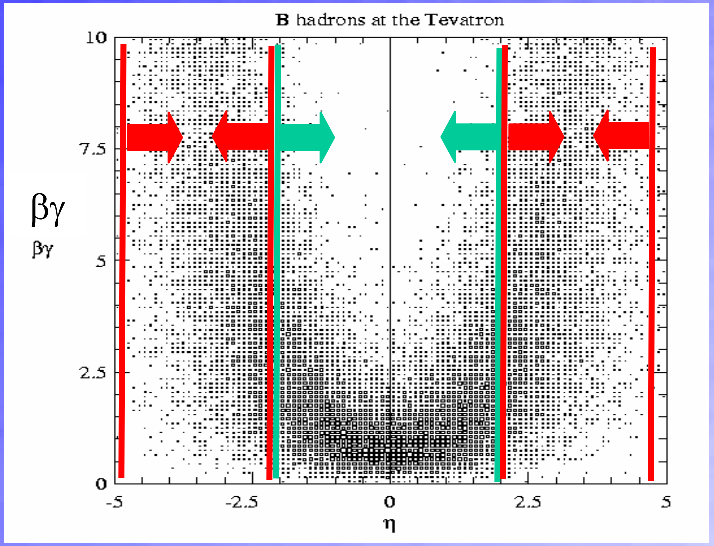
Multi-purpose experiments require large solid angle coverage.

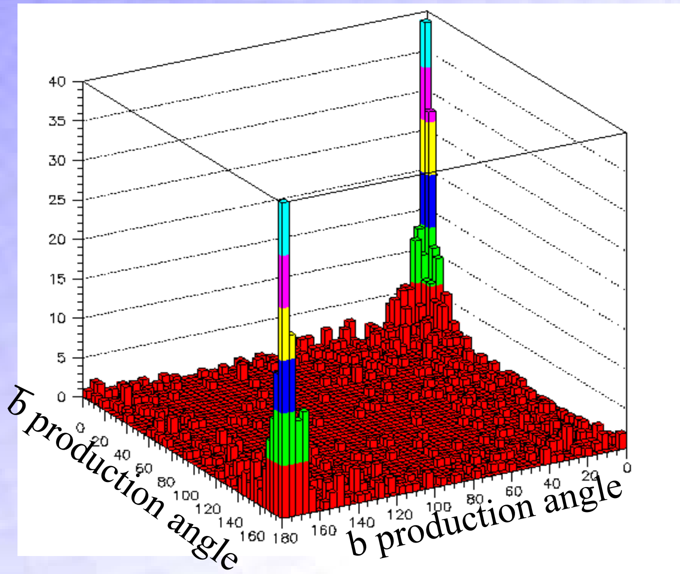
➡ Central Geometry (CDF, D0, Atlas, CMS)

Dedicated B experiments can take advantage of

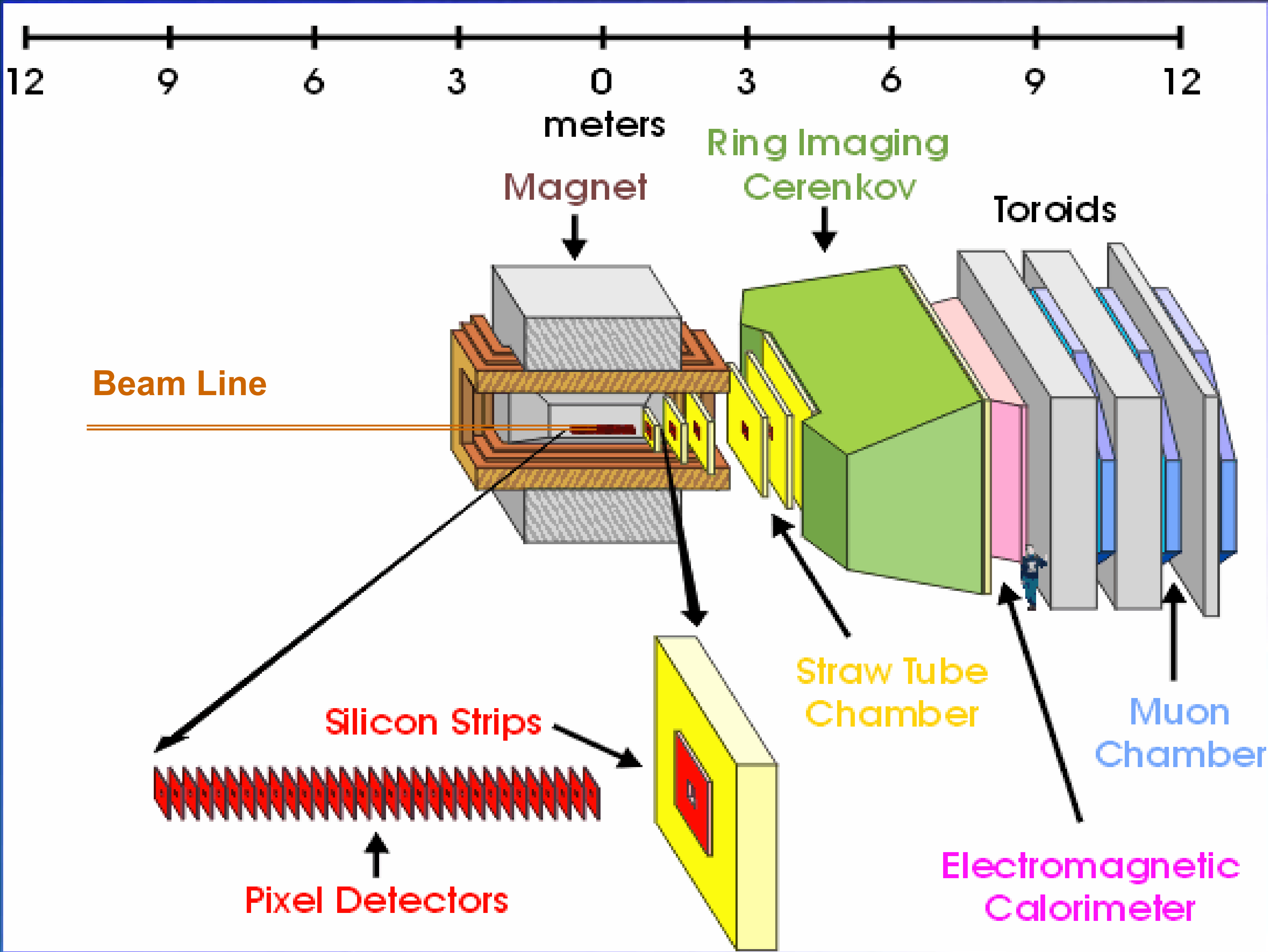
➡ Forward geometry (BTeV, LHCb)







The BTeV Detector



Pixel Vertex Detector

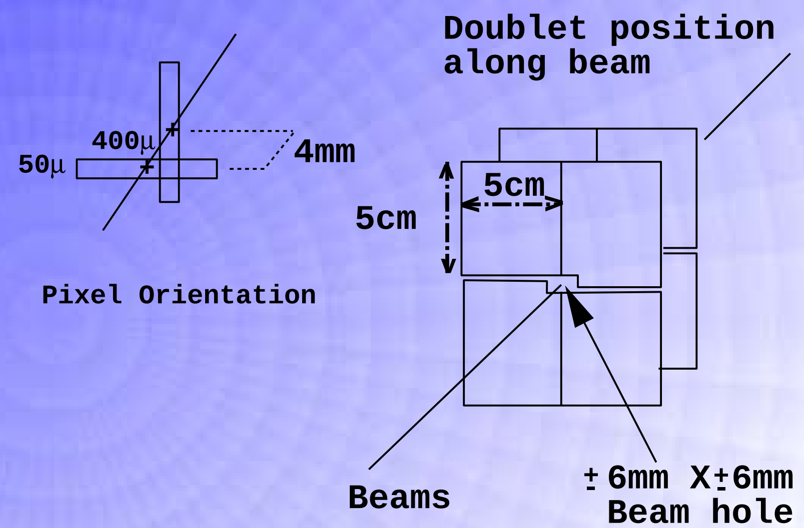
Reasons for Pixel Detector:

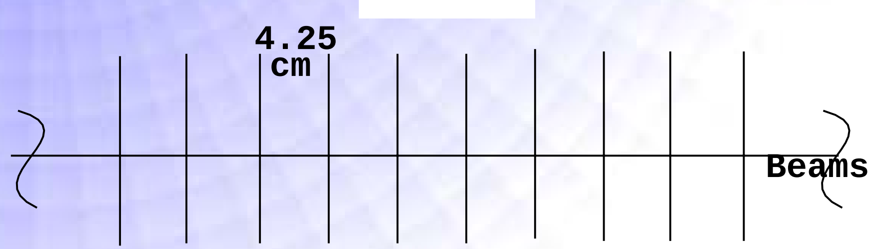
- Superior signal to noise
- Excellent spatial resolution -- 5-10 microns depending on angle, etc
- Very Low occupancy
- Very fast
- Radiation hard

Special features:

- It is used directly in the L1 trigger
- Pulse height is measured on every channel with a 3 bit FADC
- It is inside a dipole and gives a crude standalone momentum

The BTeV Baseline Pixel Detector

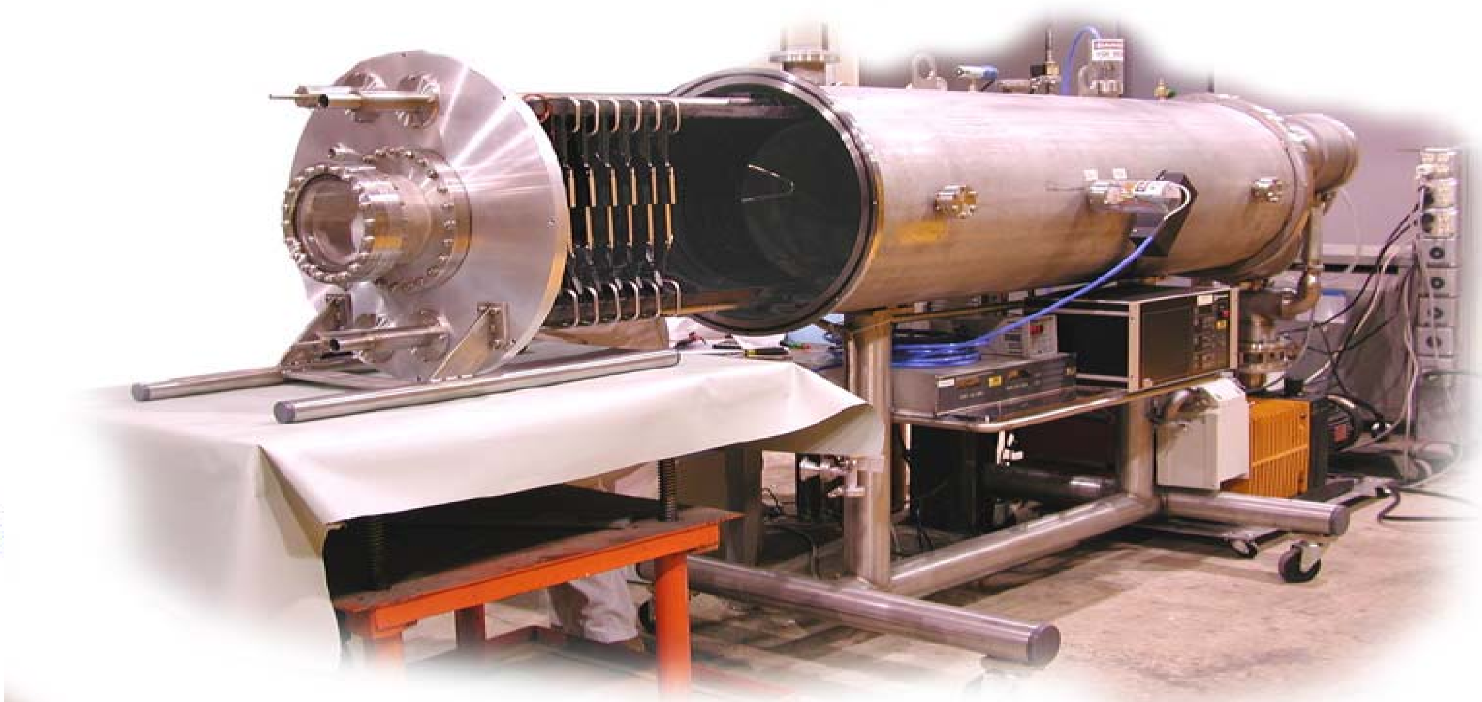




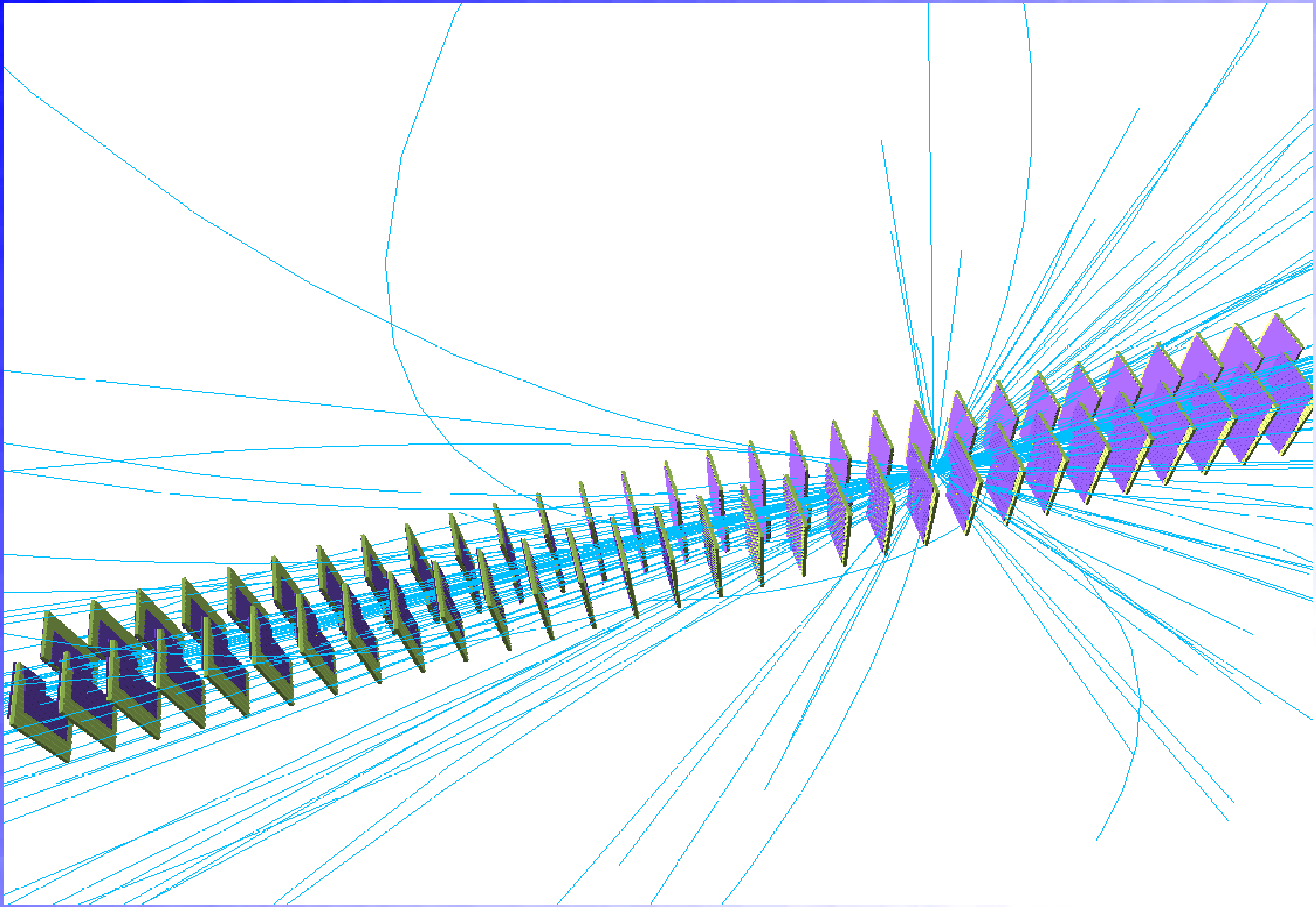
The Pixel Detector II

Half-Station Assembly

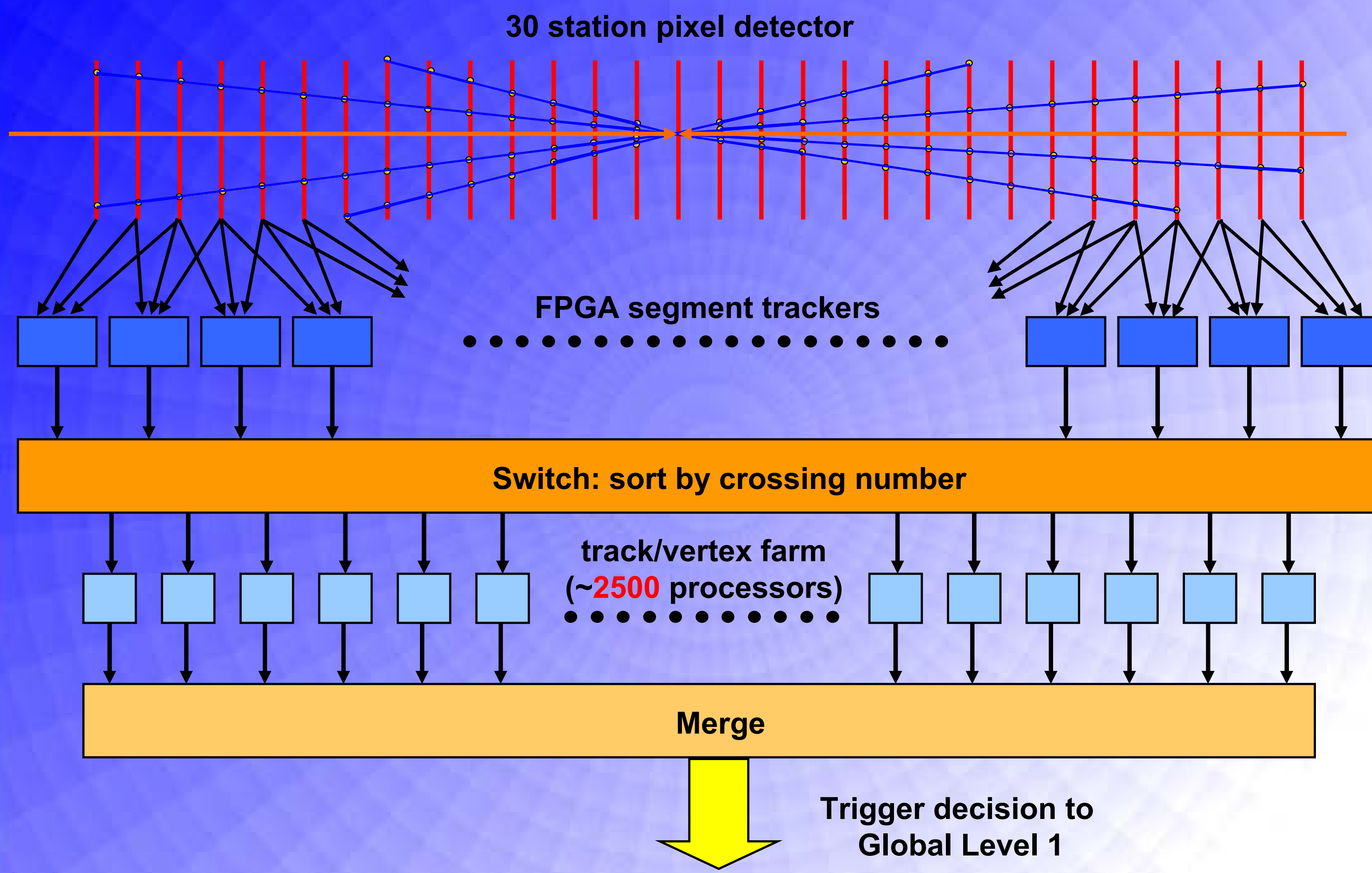
Vacuum System



Simulated B Bbar, Pixel Vertex Detector



Level 1 vertex trigger architecture



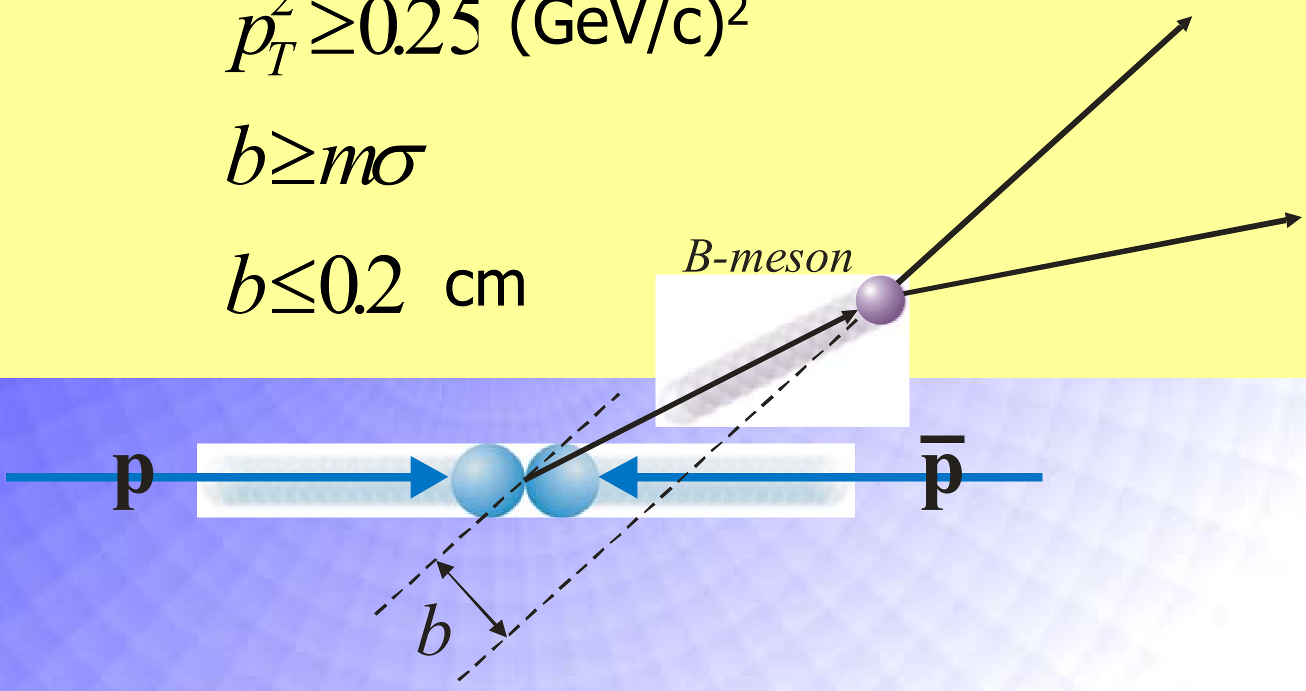
L1 vertex trigger algorithm

- Generate Level-1 accept if ≥ 2 "detached" tracks in the BTeV pixel detector satisfy:

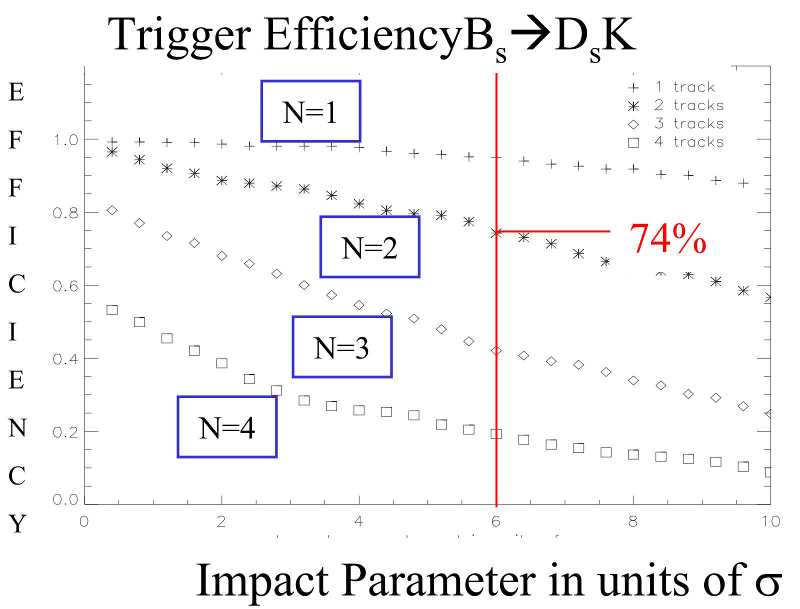
$$p_T^2 \geq 0.25 \text{ (GeV/c)}^2$$

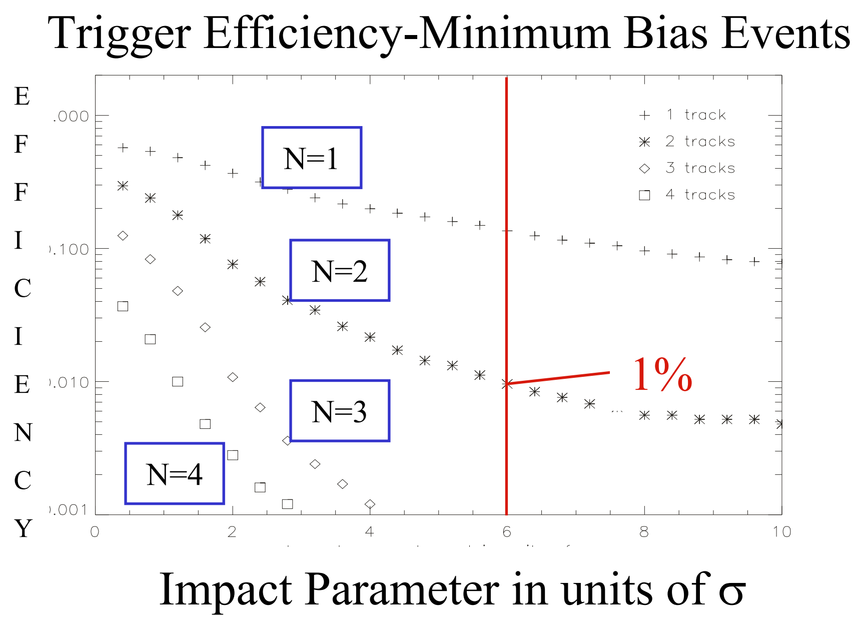
$$b \geq m\sigma$$

$$b \leq 0.2 \text{ cm}$$



Efficiencies and Tagging





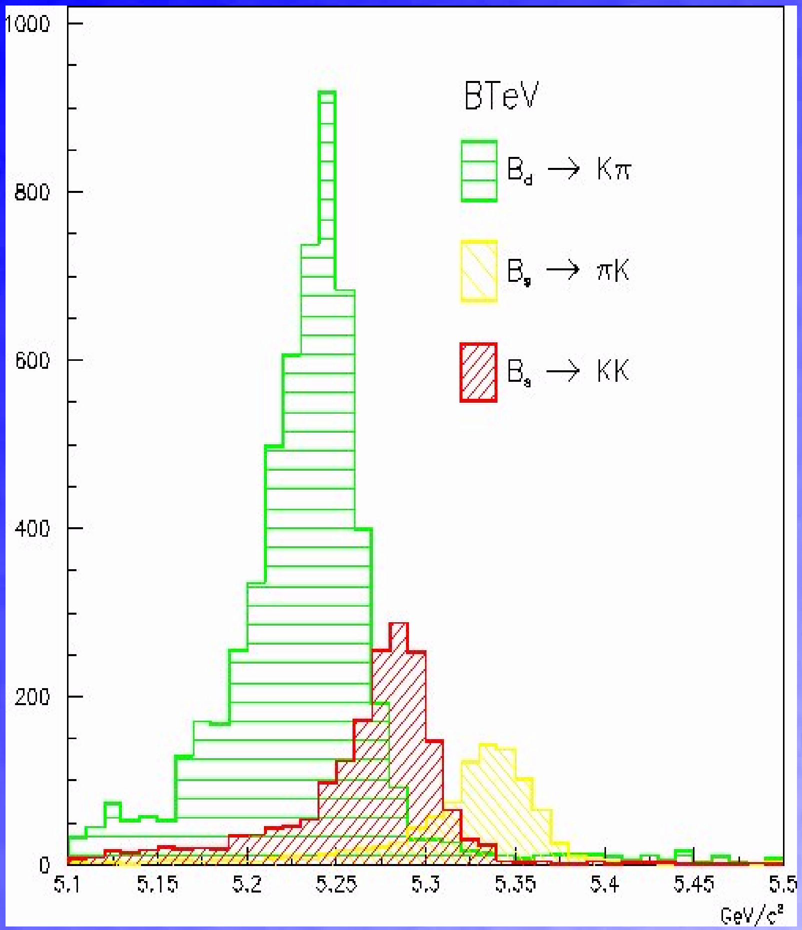
- For a requirement of at least 2 tracks detached by more than 6σ, we trigger on only 1% of the beam crossings and achieve the following trigger efficiencies for these states (<2> int. per crossing):

Decay	efficiency(%)	Decay	efficiency(%)
$B \to \pi^+\pi^-$	63	$B^o \to K^+\pi^-$	63
$B_s \to D_sK$	74	$B^o \to J/\psi\ K_s$	50
$B^- \to D^oK^-$	70	$B_s \to J/\psi K^*$	68
$B^- \to K_s\pi^-$	27	$B^o \to K^*\gamma$	40

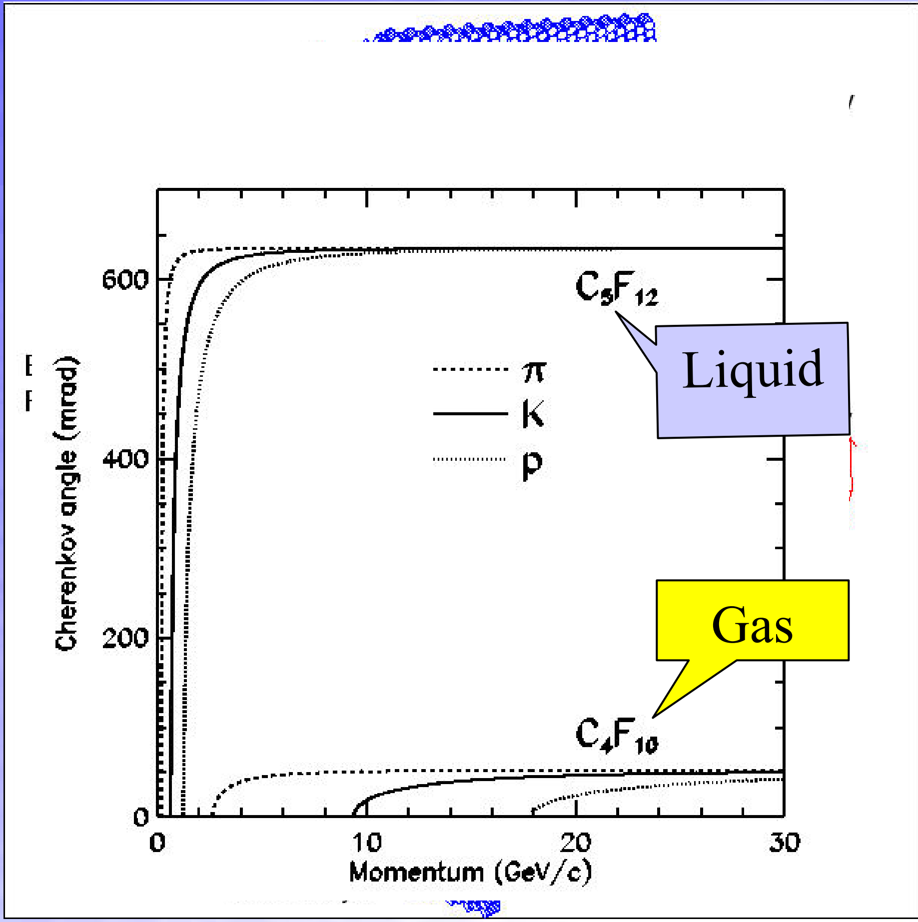
The Physics Goals

- There is New Physics out there:
  - Baryon Asymmetry of Universe & by Dark Matter
  - Hierarchy problem
  - Plethora of fundamental parameters
  - …
- B Experiments at Hadron Colliders are well positioned to:
  - Perform precision measurements of CKM Elements with small model dependence.
  - Search for New Physics via ~~CP~~ phases
  - Search for New Physics via Rare Decays
  - Help interpret new results found elsewhere (LHC, neutrinos)
  - Complete a broad program in heavy flavor physics
    - Weak decay processes, $\mathcal{B}$'s, polarization, Dalitz plots, QCD…
    - Semileptonic decays including Λ_b
    - b & c quark Production
    - Structure: B(s) spectroscopy, b-baryon states
    - B_c decays

Importance of Particle Identification

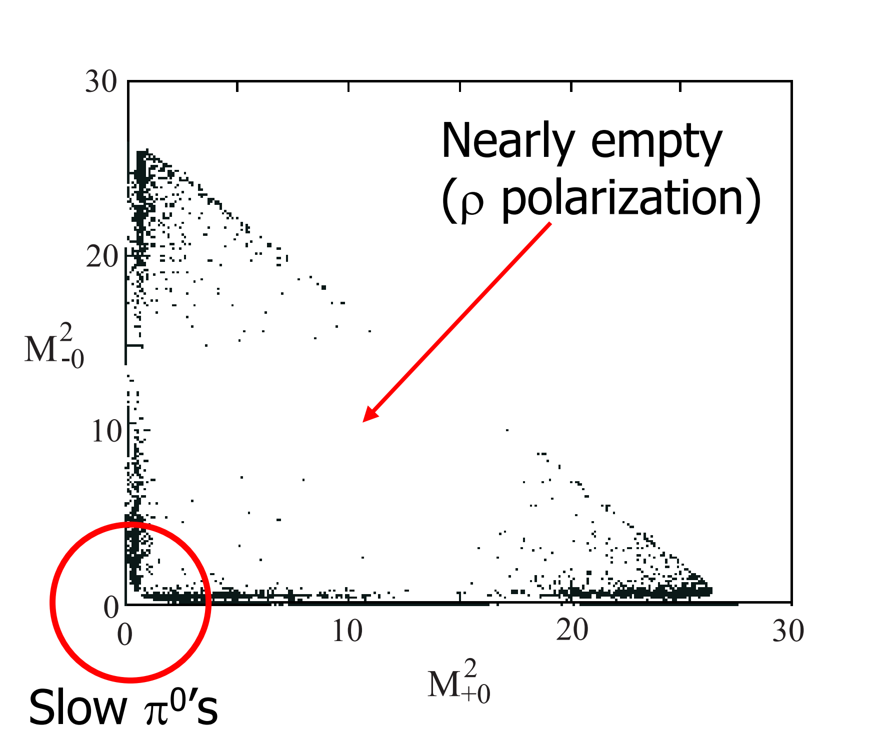


BTeV RICH Detector



Measuring α Using $B^o \to \rho\pi \to \pi^+\pi^-\pi^o$

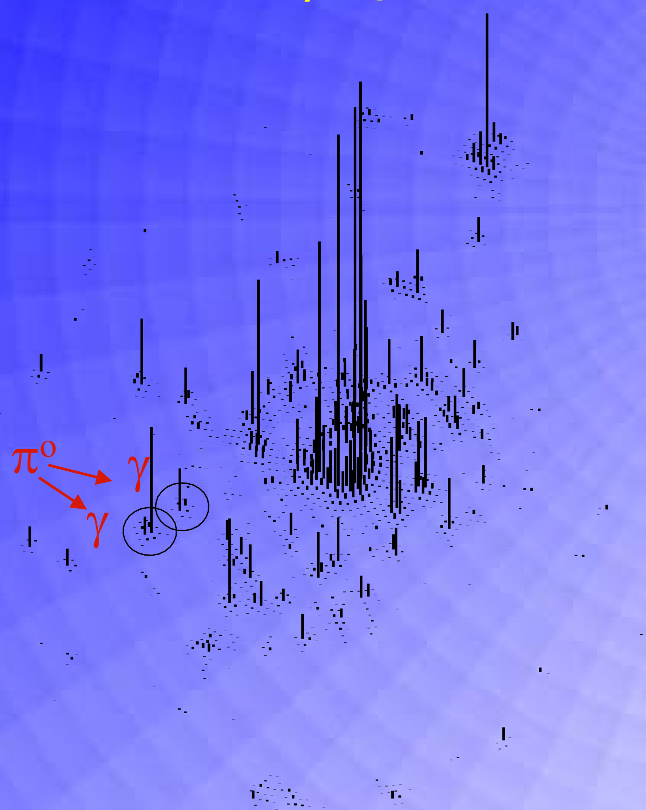
- A Dalitz Plot analysis gives **both** $\sin(2\alpha)$ and $\cos(2\alpha)$ (Snyder & Quinn)
- Measured branching ratios are:
  - $B(B^- \to \rho^o\pi^-) = \sim 10^{-5}$
  - $B(B^o \to \rho^-\pi^+ + \rho^+\pi^-) = \sim 3\times10^{-5}$
  - $B(B^o \to \rho^o\pi^o) < 0.5\times10^{-5}$
- Snyder & Quinn showed that 1000-2000 tagged events are sufficient
- Not easy to measure
  - π^0 reconstruction
- Not easy to analyze
  - 9 parameter likelihood fit

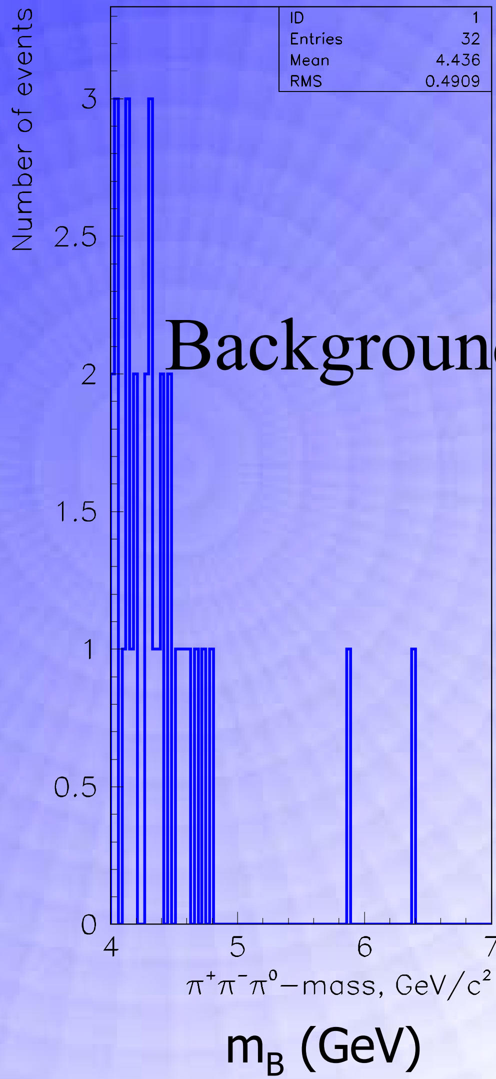


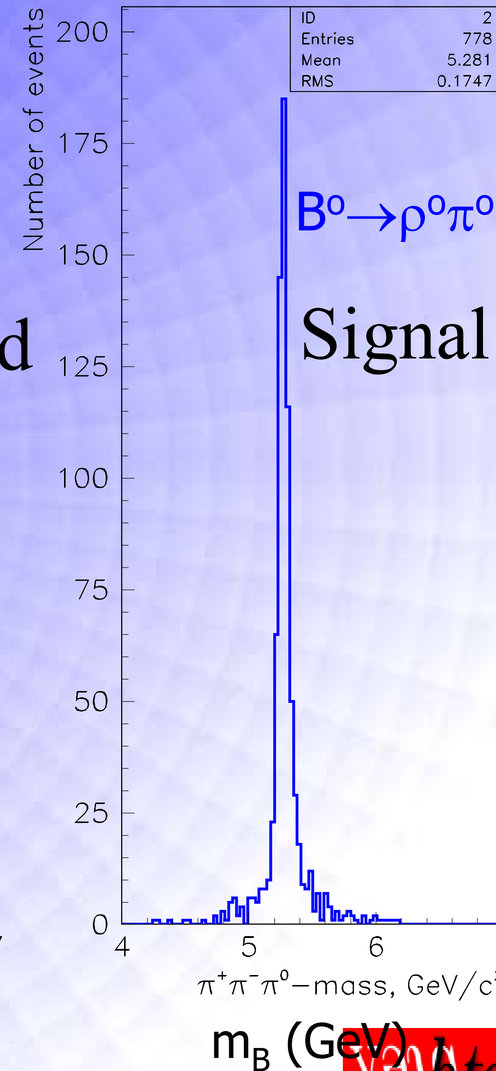
Dalitz Plot for $B^o \to \rho\pi$

Yields for $B^o \to \rho\pi$

- Based 9.9×10^6 background events
- $B^o \to \rho^+\pi^-$
  5400 events, S/B = 4.1
- $B^o \to \rho^o\pi^o$
  780 events, S/B = 0.3



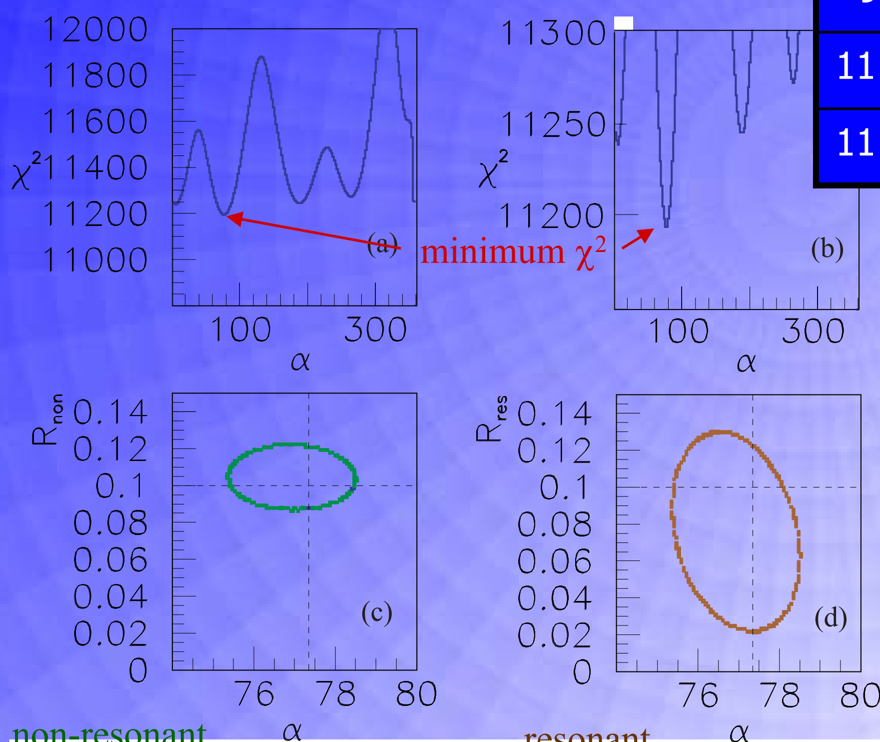




Our Estimate of Accuracy on α

- Geant simulation of $B^o \rightarrow \rho\pi$, (for 1.4×10^7 s)

α (gen)	R_{res}	R_{non}	α (recon)	Δα
77.3°	0.2	0.2	77.2°	1.6°
77.3°	0.4	0	77.1°	1.8°
93.0°	0.2	0.2	93.3°	1.9°
93.0°	0.4	0	93.3°	2.1°
111.0°	0.2	0.2	111.7°	3.9°
111.0°	0.4	0.2	110.4°	4.3°



non-resonant non-ρπ bkgrd

resonant non-ρπ bkgrd

Example:
1000 $B^o \rightarrow \rho\pi$ signal + backgrounds
With input α=77.3°

Electromagnetic Calorimeter

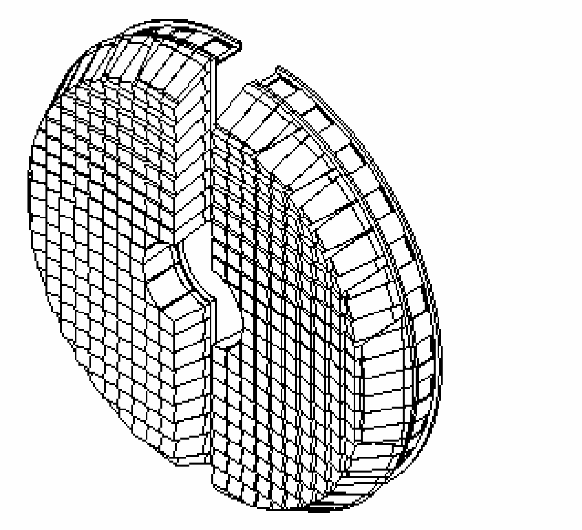
The main challenges include

- Can the detector survive the high radiation environment ?
- Can the detector handle the rate and occupancy ?
- Can the detector achieve adequate angle and energy resolution ?

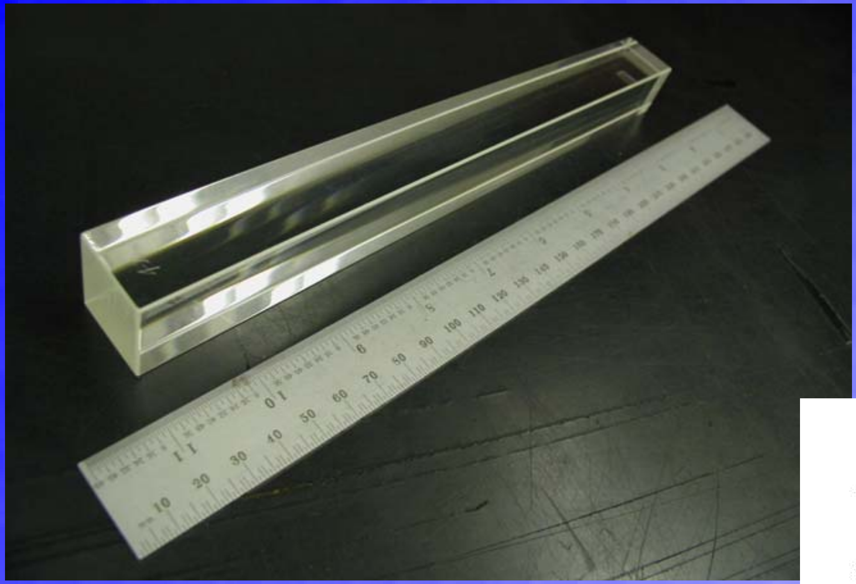
BTeV will have a high resolution $PbWO_4$ calorimeter

- Developed by CMS for use at the LHC
- Large granularity
  - Block size 2.7 x 2.7 x 22 cm^3 (25 X_o)
  - ~11000 crystals
- Photomultiplier readout (no magnetic field)
- Pre-amp based on QIE chip (KTeV)
- Energy resolution
  - Stochastic term 1.8%
  - Constant term 0.55%
- Position resolution

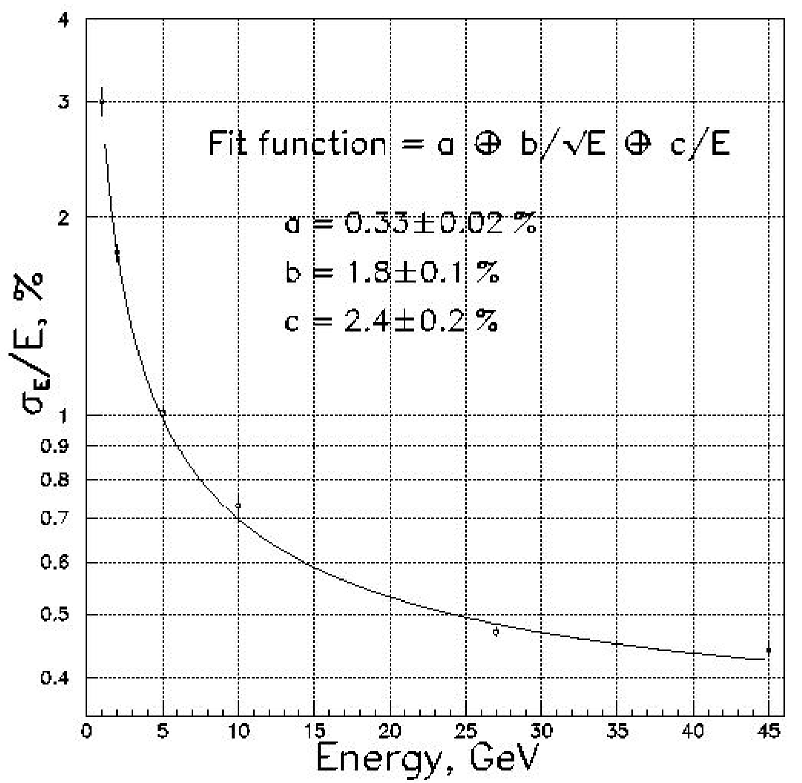
$$\sigma_x = 3526\ \mu\text{m} / \sqrt{E} \oplus 217\mu\text{m}$$



Electromagnetic Calorimeter Tests



Block from China's Shanghai Institute

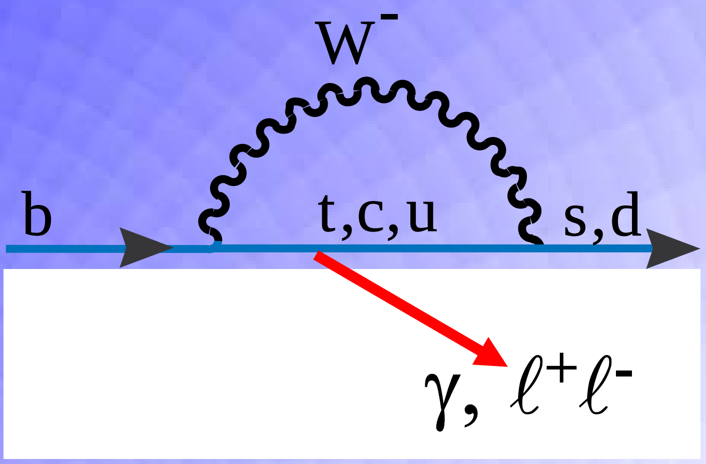


- Resolution (energy and position) close to expectations

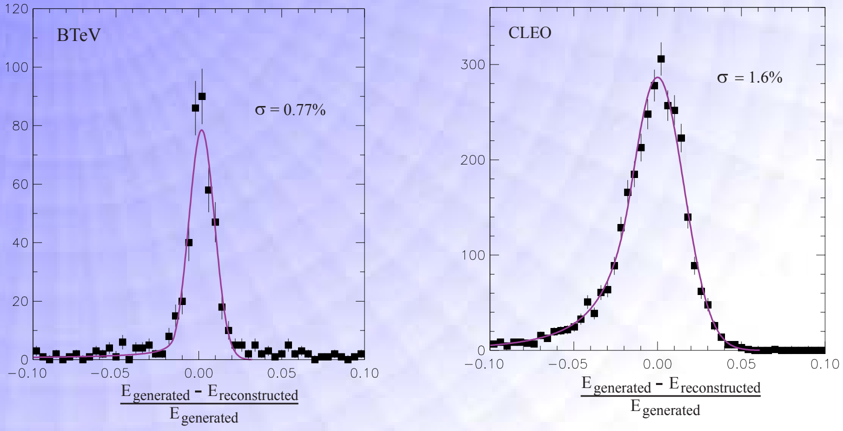
- This system can achieve CLEO/BaBar/BELLE-like performance in a hadron Collider environment!

Rare b Decays

- Search for New Physics in Loop diagrams
  - New fermion like objects in addition to t, c or u
  - New Gauge-like objects in addition to W, Z or g



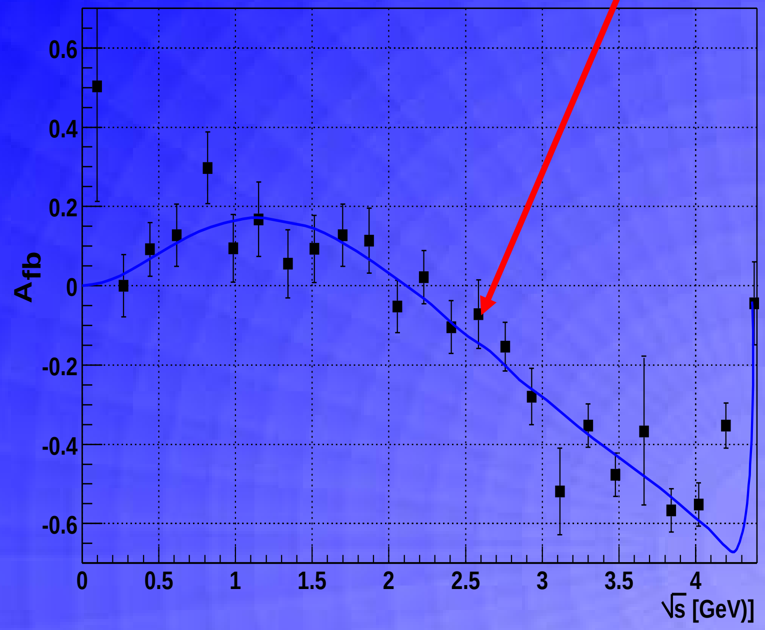
- Inclusive Rare Decays including
  - $b \to s\gamma$
  - $b \to d\gamma$
  - $b \to s\ell^+\ell^-$
- Exclusive Rare Decays such as
  - $B \to \rho\gamma$, $K^*\gamma$
  - $B \to K^*\ell^+\ell^-$ Dalitz plot & polarization

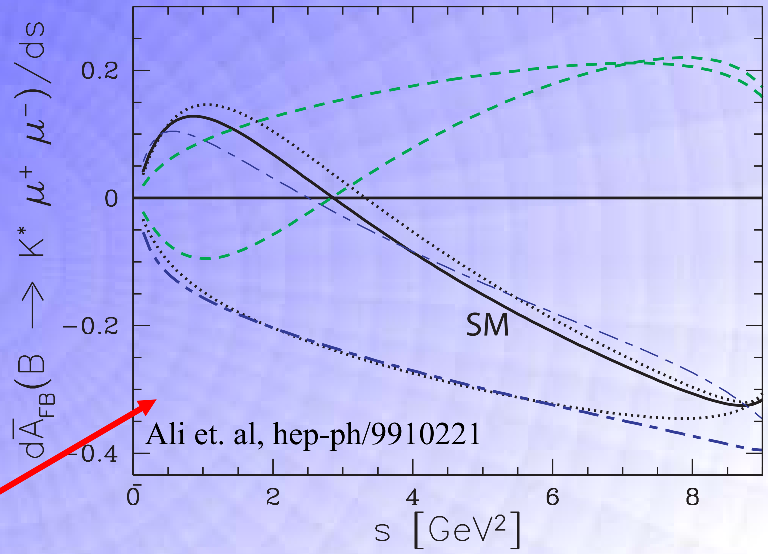


$B^o \to K^*\gamma$

Polarization in $B^o \to K^{*o}\mu^+\mu^-$

- BTeV data compared to Burdman et al calculation



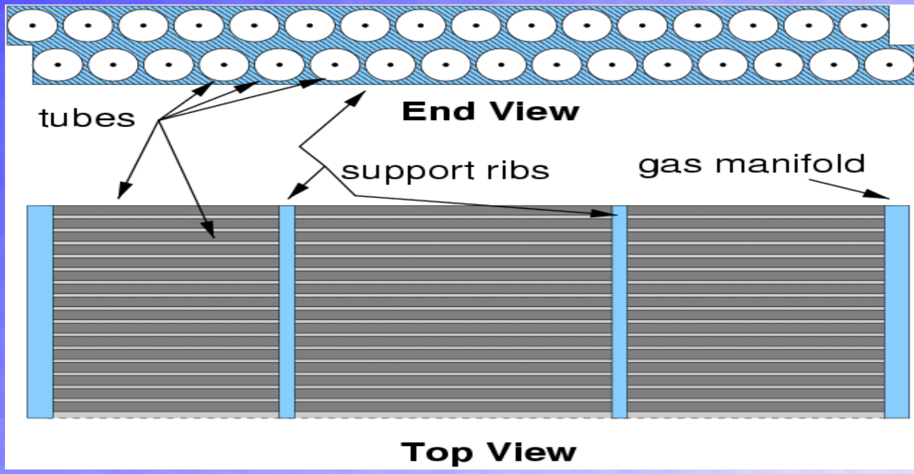


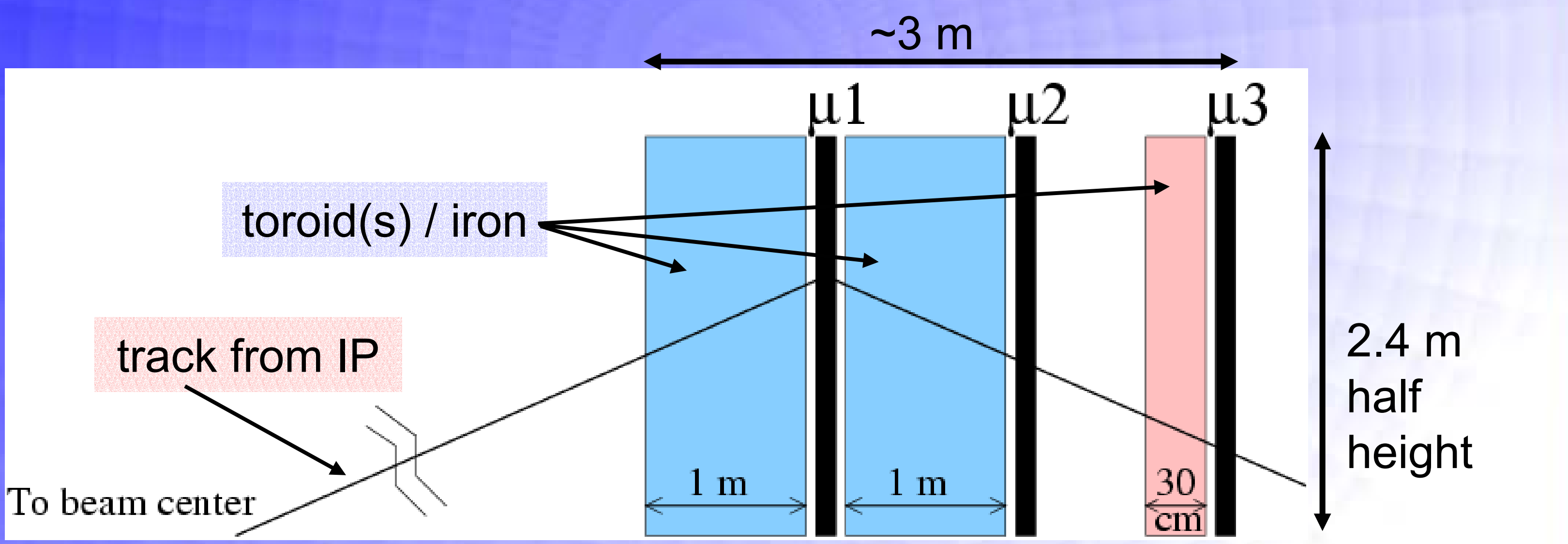
- Dilepton invariant mass distributions, forward-backward asymmetry discriminate among the SM and various supersymmetric theories. (Ali, Lunghi, Greub & Hiller, hep-ph/0112300)

- One year for $K^*\ell^+\ell^-$, enough to determine if New Physics is present

Muon System

- Provides Muon ID and Trigger
  - Trigger for interesting physics states
  - Check/debug pixel trigger
- fine-grained tracking + toroid
  - Stand-alone mom./mass trig.
  - Momentum "confirmation"
- Basic building block: Proportional tube "Planks"





Summary

- Heavy quark physics at hadron colliders provides a unique opportunity to
  - measure fundamental parameters of the Standard Model with no or only small model dependence
  - discover new physics in CP violating amplitudes or rare decays.
  - interpret new phenomena found elsewhere (e.g. LHC)
- Some scenarios are clear others will be a surprise

➡ This program requires a general purpose detector like BTeV with
  - an efficient, unbiased trigger and a high performance DAQ
  - a superb charged particle tracking system
  - good particle identification
  - excellent photon detection

Additional Transparencies

Physics Reach (CKM) in 10^7 s

Reaction	$\mathcal{B}$(B) ($x10^{-6}$)	# of Events	S/B	Parameter	Error or (Value)
$B_s \to D_s K^-$	300	7500	7	$\gamma - 2\chi$	8^o
$B_s \to D_s \pi^-$	3000	59,000	3	x_s	(75)
$B^o \to J/\psi K_S$ $J/\psi \to \ell^+ \ell^-$	445	168,000	10	$\sin(2\beta)$	0.017
$B^o \to J/\psi K^o$, $K^o \to \pi \ell \nu$	7	250	2.3	$\cos(2\beta)$	~0.5
$B^- \to D^o (K^+\pi^-) K^-$	0.17	170	1		
$B^- \to D^o (K^+K^-) K^-$	1.1	1,000	>10	γ	13^o
$B_s \to J/\psi \eta$,	330	2,800	15		
$B_s \to J/\psi \eta'$	670	9,800	30	$\sin(2\chi)$	0.024
$B^o \to \rho^+\pi^-$	28	5,400	4.1		
$B^o \to \rho^o\pi^o$	5	780	0.3	α	$\sim 4^o$

Reaction	$\mathcal{B}$(B) ($x10^{-6}$)	# of Events	S/B	Parameter	Error
$B^- \to K_S \pi^-$	12.1	4,600	1		$<4^o$ +
$B^o \to K^+\pi^-$	18.8	62,100	20	γ	Theory err.
$B^o \to \pi^+\pi^-$	4.5	14,600	3	Asymmetry	0.030
$B^o \to K^+ K^-$	17	18,900	6.6	Asymmetry	0.020

A simplified trigger comparison

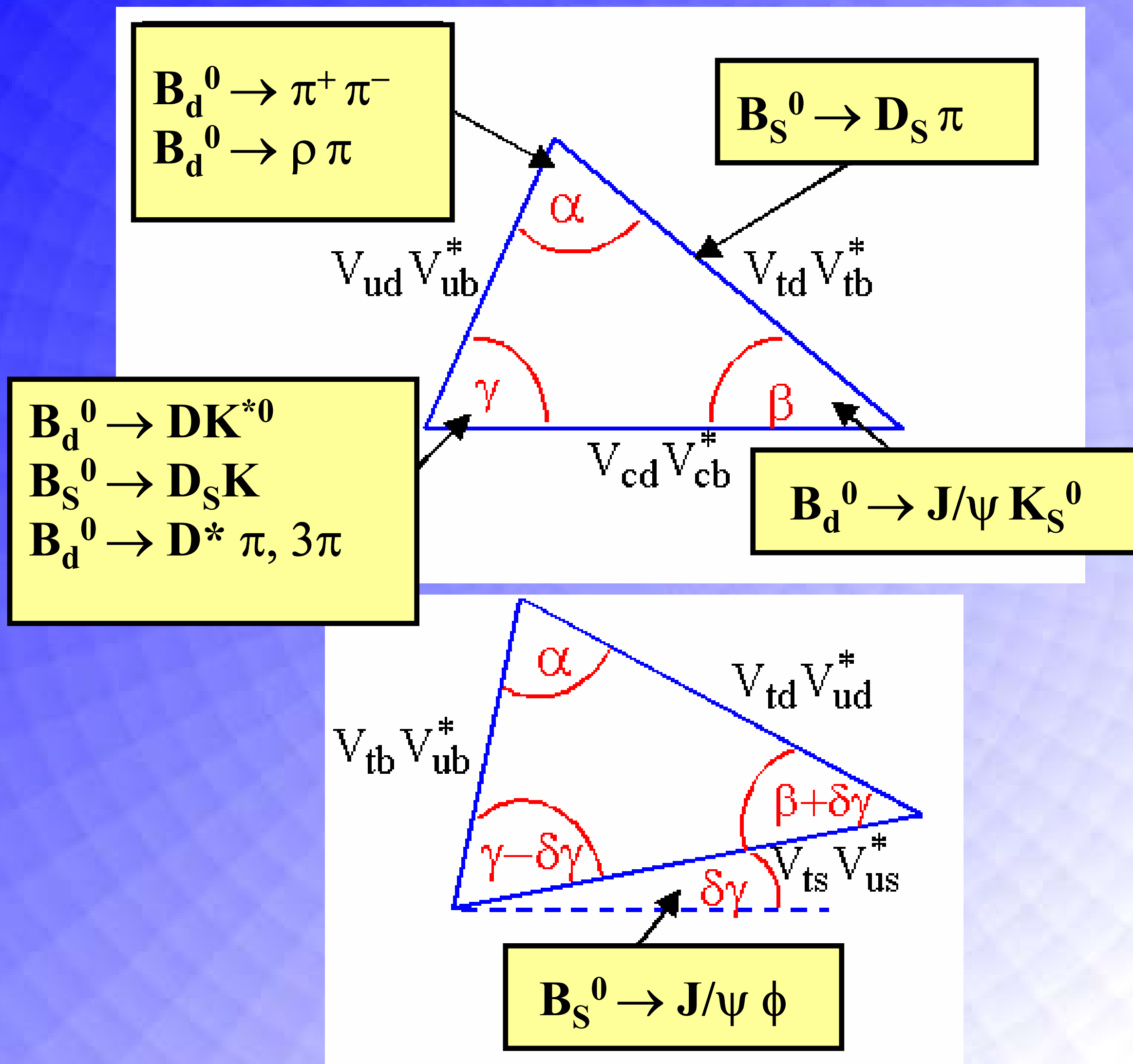
	LHCb	BTeV
High p_T, high E_T	10* MHz	
Impact parameter	1 MHz	7.6 MHz
Decay topology		80 kHz
Physics algorithms	40 kHz	
To tape	200 Hz	4 kHz

* Rate of events with visible collisions

	ATLAS	CMS
Muon trigger	40 MHz	40 MHz
$J/\psi \rightarrow l^+l^-$, $D_s \rightarrow \phi\pi$, $B \rightarrow \pi^+\pi^-$	23kHz	
Physics algorithms	1 kHz	4 kHz
To tape	10 Hz	10 Hz

From U. Egede

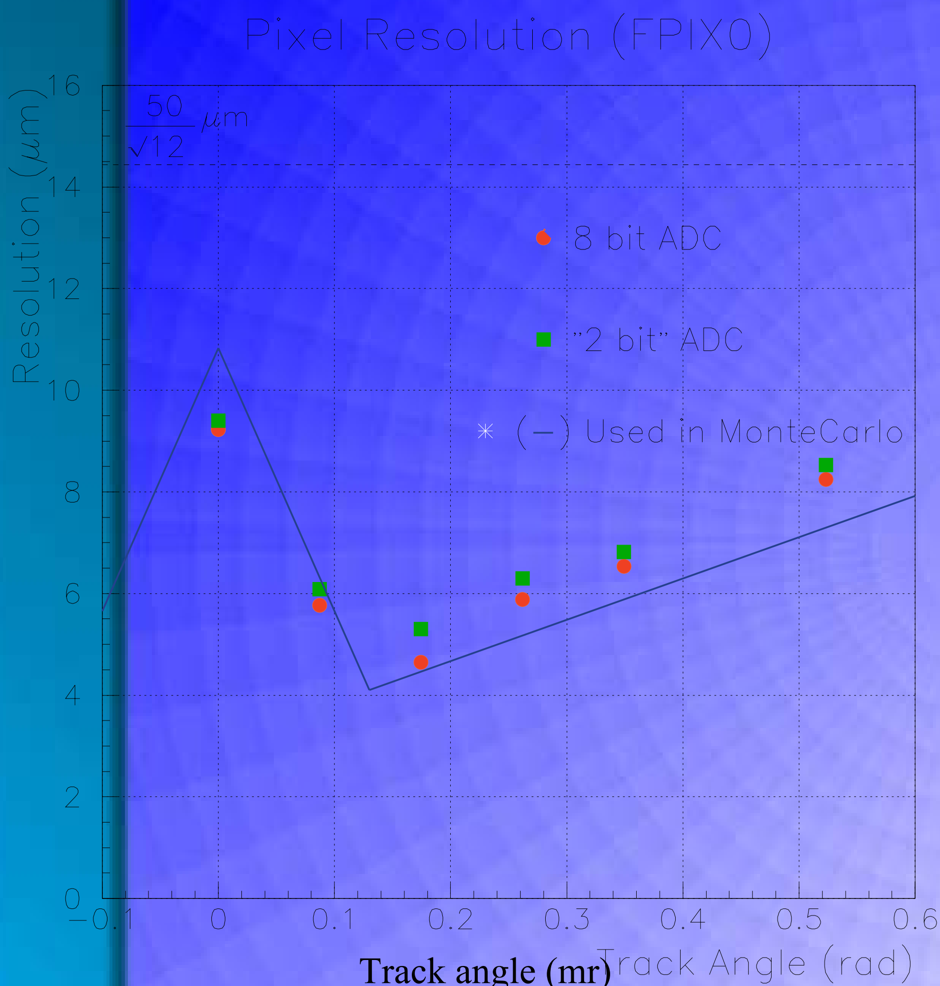
Unitarity Triangles



$$\delta\gamma = \chi$$

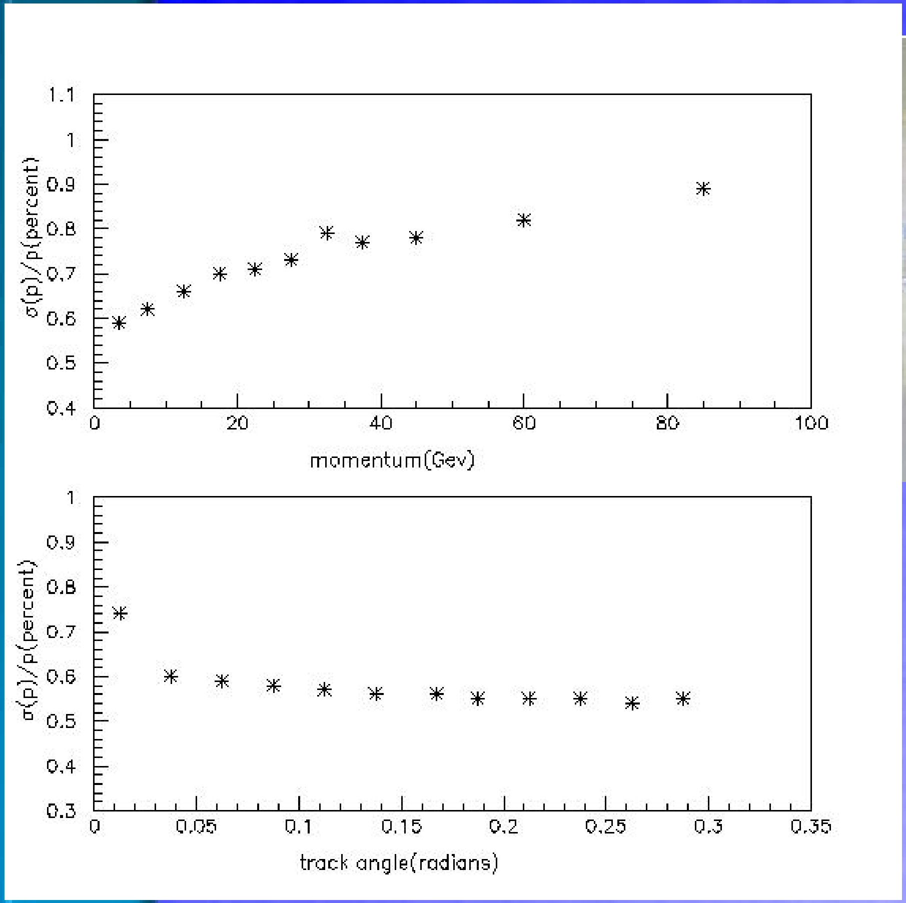
From N. Harnew

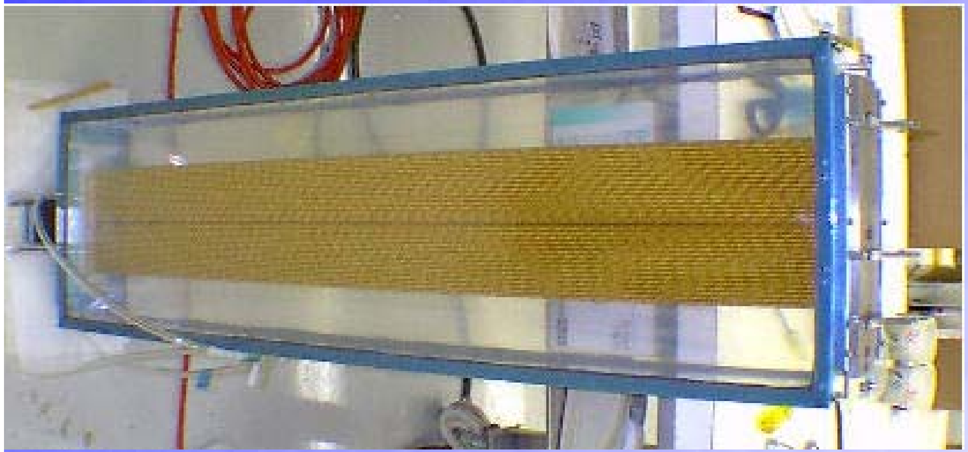
Pixel Test Beam Results



Analog output of pixel amplifier before and after 33 Mrad irradiation.
0.25μ CMOS design verified radiation hard with both γ and protons.

Forward Tracker





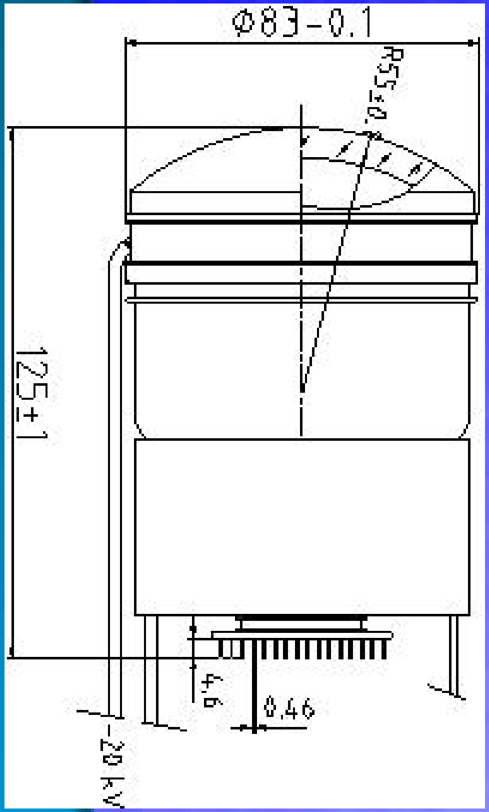
Prototype Straw tracker being constructed for FNAL beam test summer/fall 2002

Predicted performance - Momentum resolution is better than 1% over full momentum and angle range

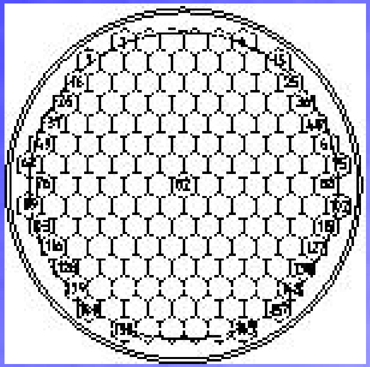
Drawing Of forward Microstrip tracker

HPD Schematic for BTeV RICH

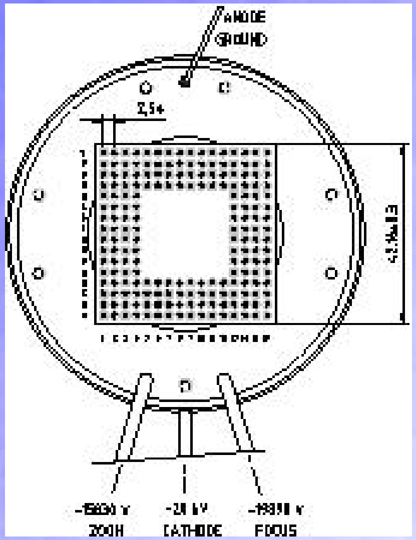
HPD Tube

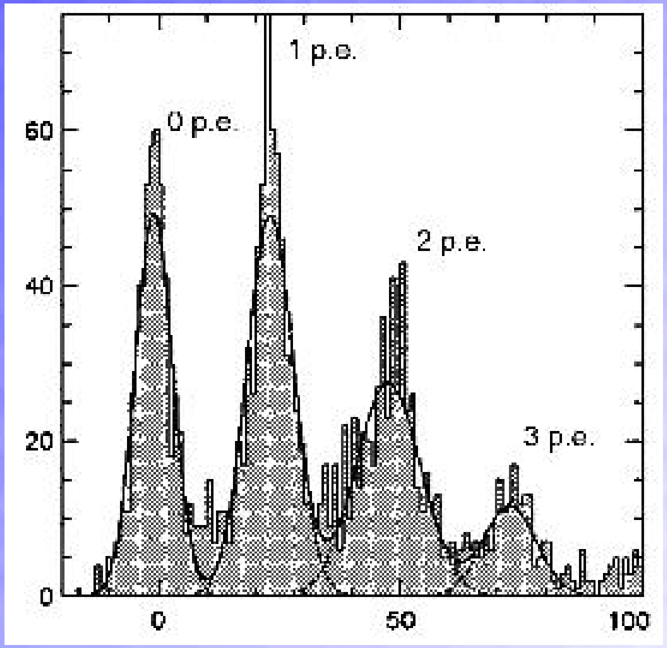


HPD Pixel array



HPD Pinout

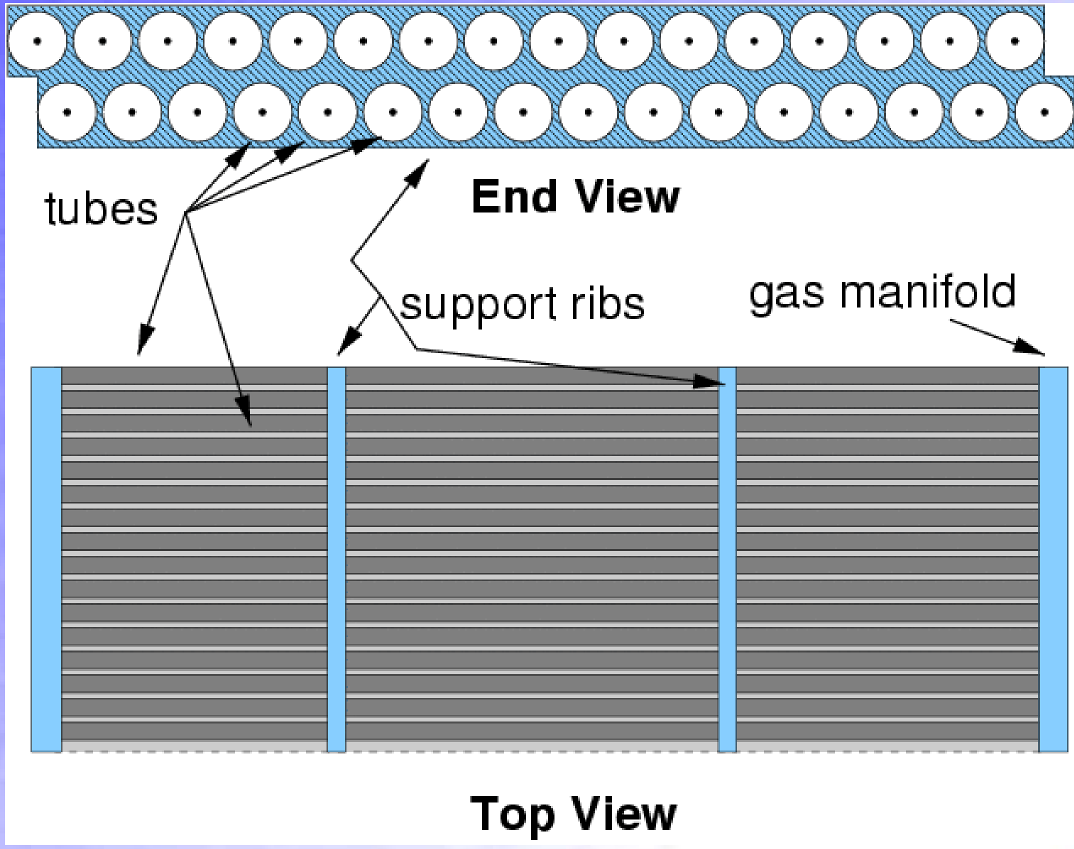




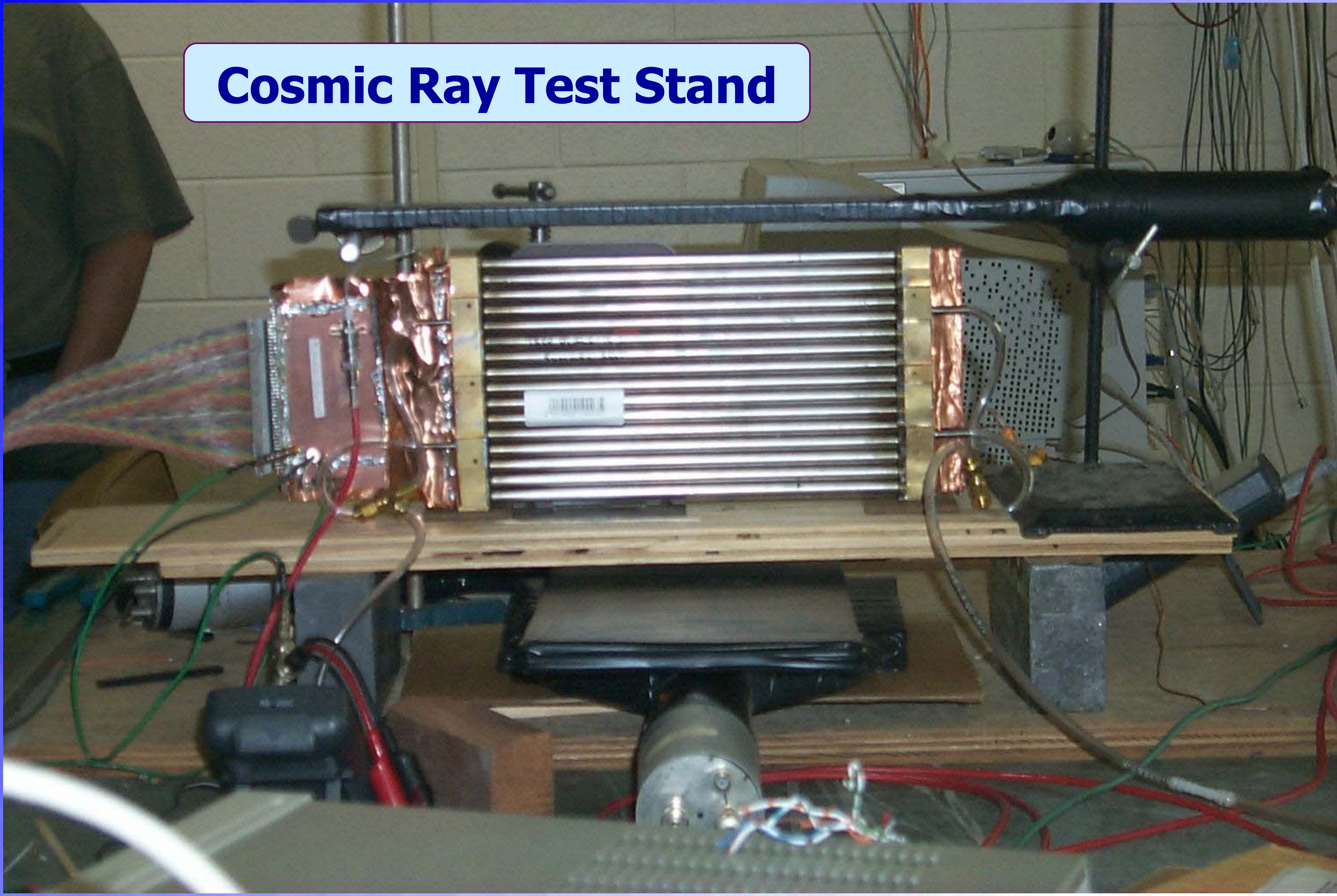
Pulse Height from 163 pixel prototype HPD. Note pedestal, 1, 2, 3 pe peaks

Prop Tube Planks

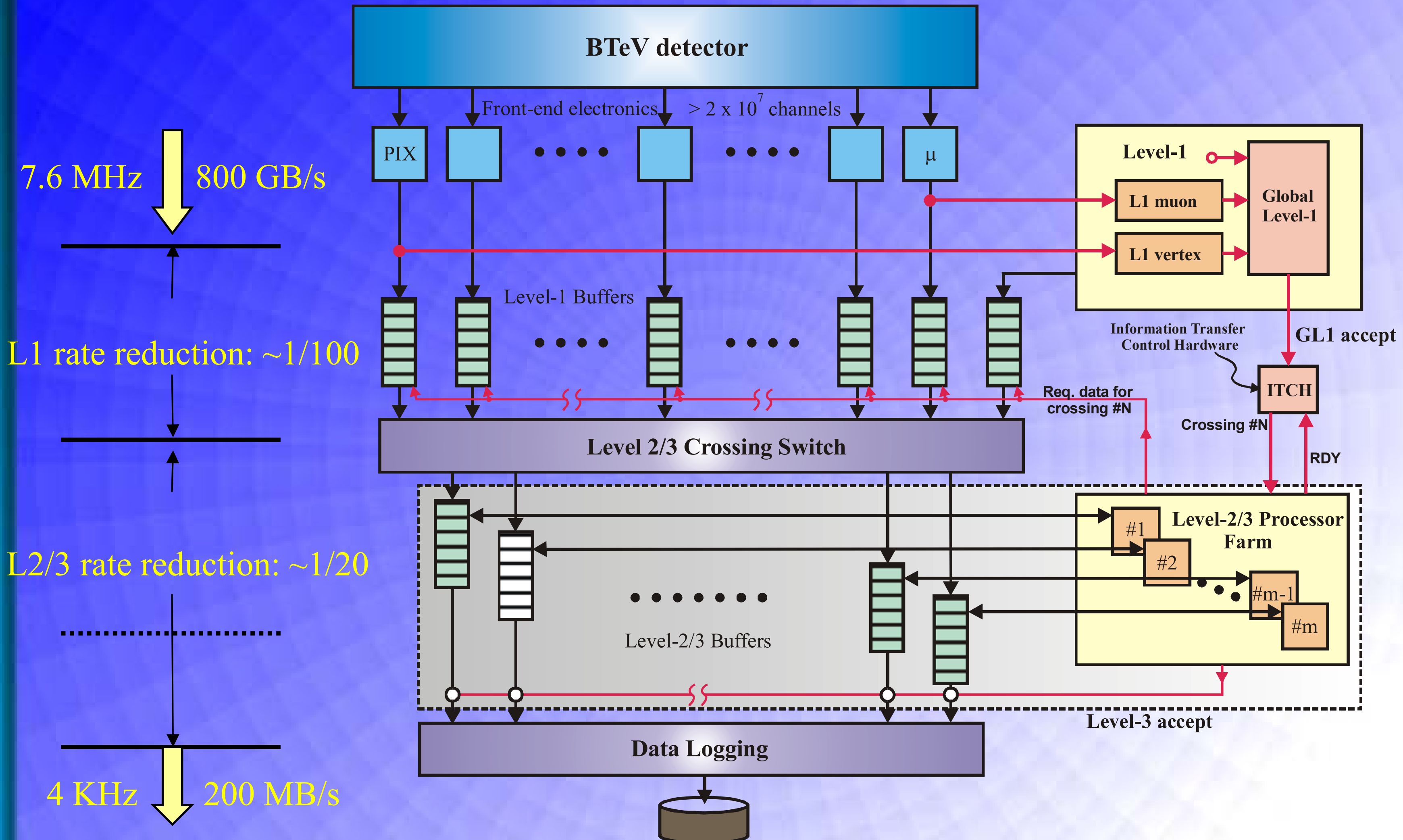
- Basic Building Block: Proportional Tube "Planks"
  - 3/8" diameter Stainless steel tubes (0.01" walls)
  - "picket fence" design
  - 30 μ (diameter) gold-plated tungsten wire
  - Manifolds are brass soldered to tubes (RF sheilding important!)
  - Front-end electronics: use Penn ASDQ chips, modified CDF COT card
  - Try "D0 fast gas" 88% Ar - 10% CF_4 - CO_2 or 50% Ar – 50% Eth.



Plank Cosmic Ray Tests



BTeV Data Acquisition Architecture



$PbWO_4$ Calorimeter Properties

Property	Value
Density(gm/cm[2])	8.28
Radiation Length(cm)	0.89
Interaction Length(cm)	22.4
Light Decay time(ns)	5(39%)
(3components)	15(60%)
	100(1%)
Refractive index	2.30
Max of light emission	440nm
Temperature	
Coefficient (%/^{o}C)	-2
Light output/Na(Tl)(%)	1.3
Light output(pe/MeV)	
into 2" PMT	10

Property	Value
Transverse block size	2.7cm X 2.7 cm
Block Length	22 cm
Radiation Length	25
Front end Electronics	PMT
Inner dimension	+/-9.8cm (X,Y)
Energy Resolution:	
Stochastic term	1.8% (2.3%)
Constant term	0.55%
Spatial Resolution:	$\sigma_x = 3526\ \mu m / \sqrt{E} \oplus 217 \mu m$
Outer Radius	140 cm--215 cm $ driven
Total Blocks/arm	11,500